ALL ABOUT THERMISTORS

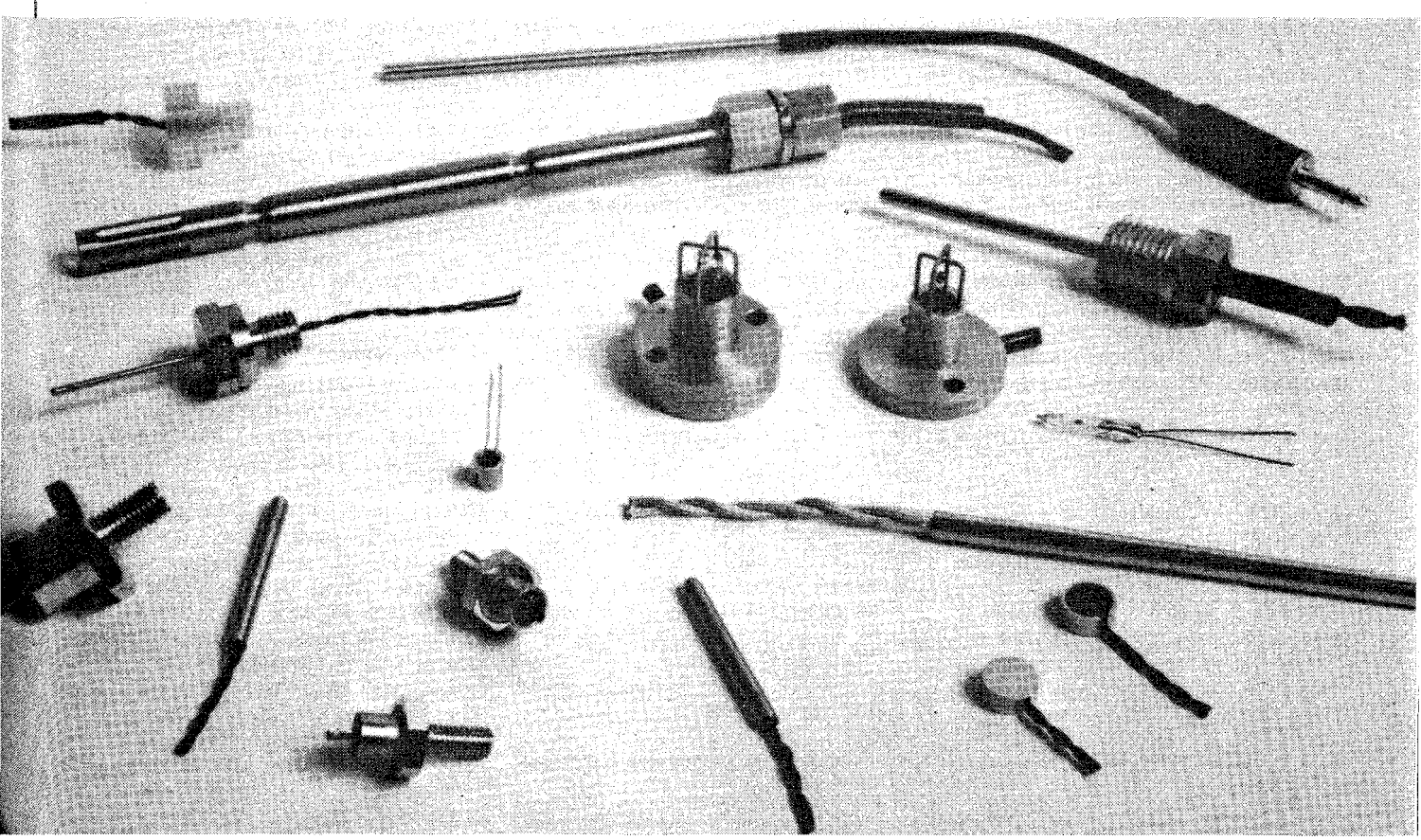
HARRY L. TRIETLEY

Last month we studied thermistor basics—what they are, how they behave, etc. This month, we'll finish our look at the basics, and then we'll show you design techniques so that put thermistors to work in your circuits.

Part 2 BEFORE WE GET TO circuit applications for thermistors, we have some basic points to mention about thermal runaway PTC thermistors, and probe assemblies.

The negative-resistance behavior makes it possible for a thermistor to go into thermal runaway and destroy itself. Figure 5 shows one of the lines from Fig. 4 (see the January 1985 issue of **Radio-Electronics** page 50) replotted with voltage on the horizontal axis, current vertical. From that plot you can see that if you connect the thermistor to a voltage source, the current will increase more rapidly than the voltage due to the thermistor's decreasing resistance. When the voltage becomes high enough to enter the negative-resistance part of the curve, the resistance will decrease because the thermistor is getting hotter. That results in increased current, heating the thermistor even more, increasing the current more, etc. If there is no current limiting, the thermistor will continue to heat until it destroys itself. Always be careful, when connecting a thermistor to a voltage source, to either limit the voltage to safe values or else provide some means to limit the current. We would point out that the curves we've just described depend very much on the application and must be determined experimentally. Changing the surrounding temperature, connecting the thermistor to a heat sink, changing the air flow, or putting it in an enclosure will create a new set of curves.

The fact that a thermistor heats itself when power is applied is a drawback when measuring temperature—the power must be kept well below a milliwatt to avoid errors. In other uses, however, thermistors are purposely self-heated. For example, if you self-heat a thermistor well above the surrounding air temperature and then increase the air flow, its temperature will drop, increasing its resistance. You now have a sensor to detect wind or air cur-



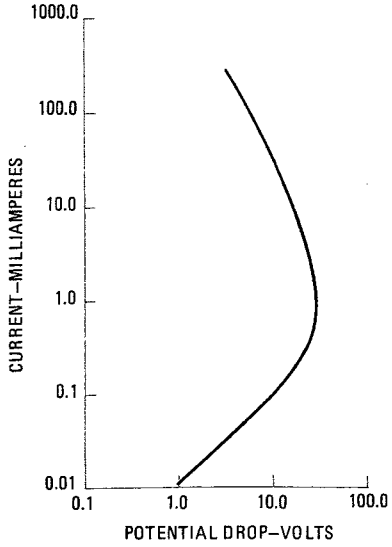


FIG. 5—A THERMISTOR MAY ENTER THERMAL RUNAWAY if neither voltage nor current are limited.

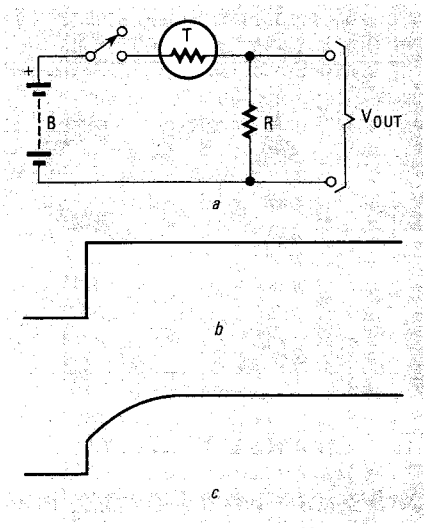


FIG. 7—CREATING A TIME DELAY is one popular use for thermistors.

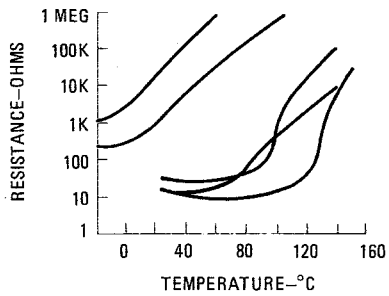


FIG. 8—RESISTANCE-TEMPERATURE CURVES for five typical PTC thermistors.

rents. Likewise, a self-heated thermistor's temperature will drop when it comes in contact with liquid, making it useful as a liquid-level sensor.

Response time

Suppose you suddenly move a thermistor from one temperature to another. Like any thermometer, it will take a while to respond. The mass of the thermistor must heat up or cool down to match the surrounding temperature. The response will look fairly much like an exponential R-C time response as shown in Fig. 6, with the 63% response time indicated by time constant, τ. For small disc or bead thermistors, the time constant will be one to several seconds. Large thermistors respond more slowly: One-inch discs may take two minutes or more. Of course, a thermistor's response will be faster in liquid or in moving air than in still air.

It also takes some time for a thermistor to heat itself when power is applied. Figure 7 shows what happens if a thermistor and resistor in series are connected to a voltage source. At first, the thermistor's resistance is high, limiting the output. If enough power is applied, it slowly heats up, dropping its resistance and raising the output until thermal equilibrium is reached. Thermistors are often used in this way to create delay times or to protect against sudden inrush currents. We will study such applications in more detail a bit further on in this article.

PTC thermistors

As we mentioned at the beginning of this article, there are two distinctly different types of positive temperatures coefficient (PTC) thermistors: those sintered from powdered metal compounds and those made from silicon. The most common of the sintered types are those made from barium titanate, with various doping materials added. Thermistors of that type have resistances that increase with temperature as shown in Fig. 8. Note that the vertical scale is logarithmic—the increase in resistance is very rapid.

PTC thermistors are sold in most of the same configurations as NTC's, including small and large discs, washers, and rods with and without leads and coatings. The R-T curves are highly nonlinear and, more important, have a sudden increase in resistance over a narrow temperature range. Such devices are especially useful as temperature switches or temperature limiters, particularly when high precision is not required. Larger PTC thermistors can switch moderate amounts of power; for example, enough to control a series relay. Simply place the relay and PTC thermistor in series with a voltage source and the relay will drop out somewhere along the steep portion of the curve. The switching point is controlled by varying the doping used in the thermistor.

PTC thermistors also can be used as current limiters. When their current becomes too large they will self-heat to the point where their resistance increases rapidly.

An interesting use of larger PTC thermistors is as self-regulating heaters. When power is applied, the thermistor will heat itself until it reaches the steep portion of the curve, at which point the current will decrease rapidly. A fairly constant temperature will be maintained regardless of changes in the ambient temperature or thermal load. One manufacturer has created a heater for liquid-crystal displays by epoxying several PTC thermistors to a metal strip. The strip is glued or clamped to the back of an LCD and connected to a 24-volt power source. When the LCD is warm, the heater will draw very little current. If the temperature drops, however, the thermistors will self-heat until they warm the assembly back up to their switching temperature. It seems that some similar arrangement will have to be used in automobiles if LCD's are used for dashboard displays. PTC thermistor material is also formed into custom designed shapes to form self-regulating heating elements in appliances such as hot-glue guns.

Silicon PTC thermistors do not have much in common with either PTC or NTC sintered thermistors—at least in their manufacturing process. They are made from single-crystal silicon wafers (like those used to make IC's) with dopants (impurities) added to produce the proper resistance.

Figure 9 shows a typical R-T curve for silicon PTC thermistors. They generally are sold in the same resistance values (at 25°C) as standard 10% resistors; that is, 10, 12, 15, 18, and 22 ohms etc, in values from 10 ohms to 10 kilohms. As you can see from the curve they are fairly linear and much less sensitive than other thermistors, about 0.7 percent per degree C. The exact shape of the curve is affected by the dopant added; hence, different resis-

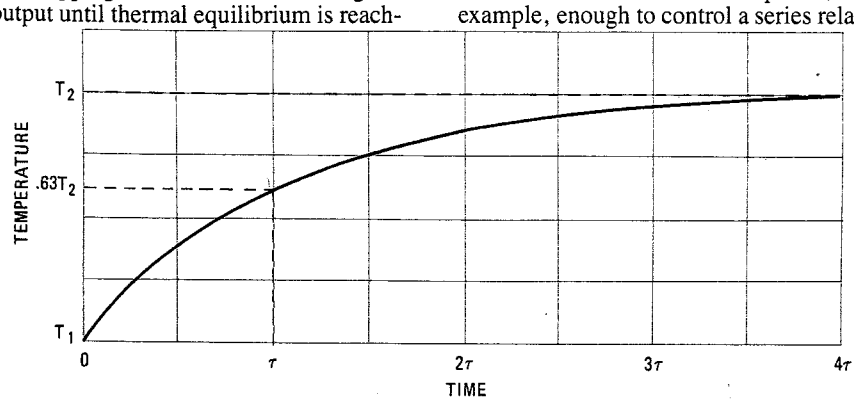


FIG. 6—A THERMISTOR'S RESPONSE to a sudden temperature change is approximately exponential.

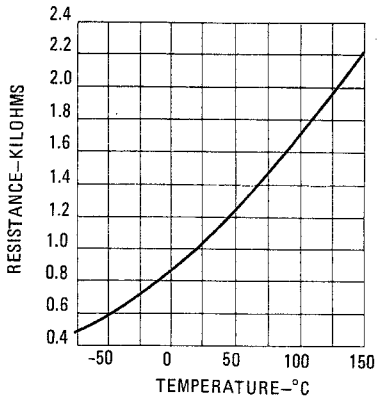


FIG. 9—SILICON PTC THERMISTORS have nearly linear resistance-temperature characteristics.

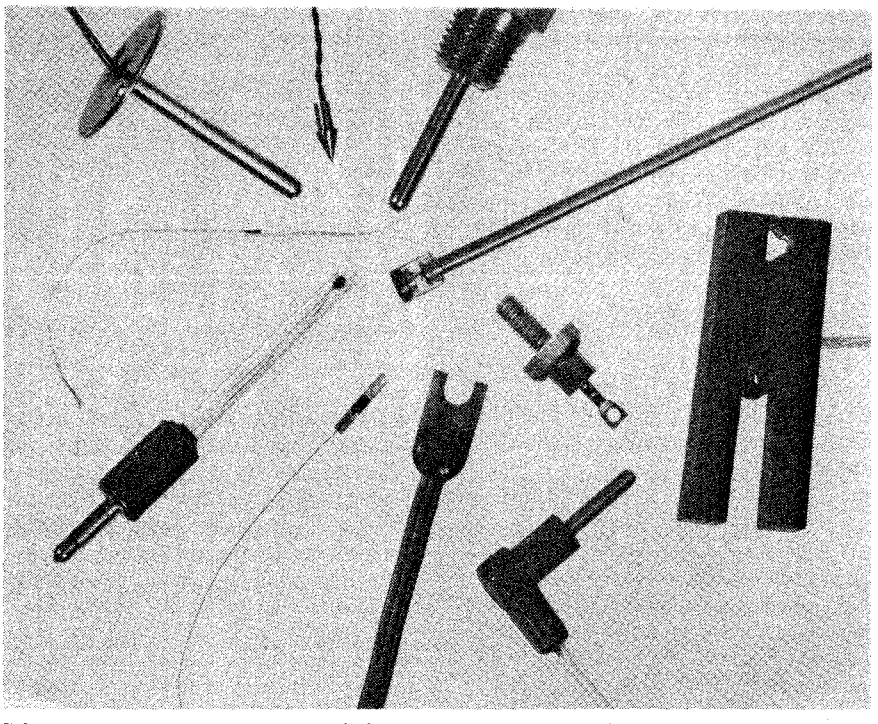


FIG. 10—A WIDE VARIETY OF THERMISTOR mountings and assemblies are available.

tance values have slightly different curves.

The operating range of silicon PTC thermistors runs from around −80°C (−112°F) to +150 or 200°C (+302 to 392°F), depending on the style and manufacturer. Tolerances are generally ±10% to ±20% (at 25°C) although tolerances to ±1% are available. Keep in mind that that is poorer than similarly specified NTC thermistors: Their 0.7%/°C sensitivity means that a ten percent error equals 14°C (as opposed to 2.5°C for a 4%/°C NTC thermistor). Again, the tolerance is wider at higher and lower temperatures.

Silicon PTC thermistors are most often sold in diode or transistor-type packages. They also are available mounted on two parallel leads and covered with epoxy, similar to small disc thermistors.

Thermistor probe assemblies

An unprotected thermistor is poorly suited to most temperature measurements. You can't dip it in water or any other conducting liquid since the liquid will shunt the leads, producing false readings. Also, except for hermetically sealed glass units, the liquid will eventually creep into the thermistor, most likely finding a path in minute voids between the leads and the epoxy coating. Nonconductive liquids may attack or soften the epoxy; corrosive liquids may destroy the leads. Even continued exposure to high-humidity air may eventually produce electrical leakage inside the thermistor. Sealing the thermistor can also provide protection for mechanical ruggedness.

Thermistors are often mounted inside temperature probes, such as those seen in Fig. 10. Usually, the probe consists of a length of stainless steel, glass or other tubing welded closed at the measurement end. The thermistor is soldered to a length of wire or cable and inserted into the probe, generally with a bit of epoxy in the probe tip to give mechanical strength and to create better thermal contact with the probe. Additional epoxy is used to seal the back end. A probe may be simply a "straight stick" for laboratory use, or it may be welded to pipe-threaded fittings or other mountings for permanent installation.

Of course, thermistors may be mounted in other ways. For example, they may be epoxied into a drilled-out bolt for installation into a tapped hole. The possibilities are limited only by your imagination. For commercial and OEM customers, many thermistor manufacturers will build their thermistors into probes or other assemblies to meet users' needs.

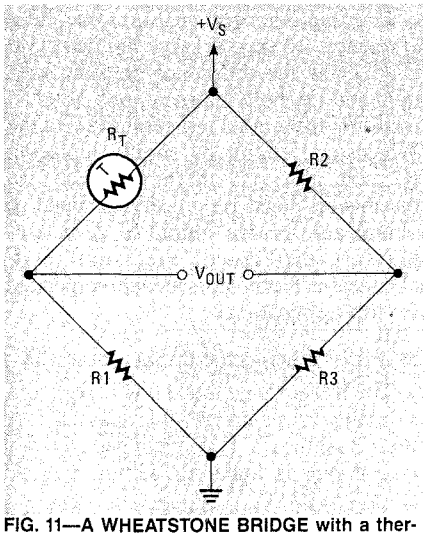


FIG. 11—A WHEATSTONE BRIDGE with a thermistor arm will produce an output that increases with temperature.

Bridge circuits

If we connect an NTC (*N*egative *T*emperature *C*oefficient) thermistor in a Wheatstone bridge as shown in Fig. 11, we can generate a voltage that increases with temperature. If we choose our resistors properly, we can insure that the voltage will vary fairly linearly with respect to temperature (if only over a narrow temperature range).

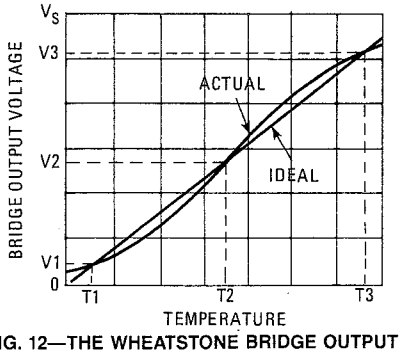


FIG. 12—THE WHEATSTONE BRIDGE OUTPUT is fairly linear near the middle of its range.

Figure 12 shows the output voltage of a Wheatstone bridge as a function of temperature. Note that the curve is S-shaped, approaching—but never reaching—the supply voltage at high temperatures (low thermistor resistance). The sensitivity is highest near the midrange, where the thermistor resistance is close to the resistance of R1.

While it is not possible to change the basic shape of this curve, you can choose R1 so that the center of your temperature range is on the most linear (center) portion of it. For narrow temperature ranges (not more than about 20 °C), you can achieve a quite linear output by making R1 equal to the thermistor's resistance at the center of the temperature range. Linearity becomes poorer as the temperature range gets wider.

Designing for best possible linearity requires a bit of algebra, but it's not at all difficult. Looking again at Fig. 12, note the "ideal" straight line drawn on top of the actual curve. The two cross at three temperatures, T1, T2, and T3. Best linearity is achieved when T1 and T3 are the end points of the desired temperature range and T2 is exactly in the middle. The equation for the output voltage is:

$$V_{OUT} = \frac{Vs \times R1}{R1 + R_T}$$

We wish to select R1 so that: V3 − V2 = V2 − V1 when T3 − T2 = T2 − T1

All this may be solved algebraically to give us:

$$R1 = \frac{R_{T1}R_{T2} + R_{T2}R_{T3} - 2R_{T1}R_{T3}}{R_{T1} + R_{T3} - 2R_{T2}}$$

If you know the thermistor's resistance (R_{T1}, R_{T2}, and R_{T3}) at temperatures T1, T2, and T3, simply substitute them in this equation to find the optimum value of R1. The thermistor's values may be taken from the manufacturer's data or by measurement at the three temperatures.

You still need to choose R2, R3, and the supply voltage, V_S. Choosing the resistors is easy—set R3 equal to R1, then make R2 equal to the thermistor's resistance at the temperature where you want zero output voltage from the bridge. You may want to make R2 adjustable for calibration purposes.

The supply voltage, V_S, determines the output sensitivity (millivolts-per-degree). You may need to do some trial-and-error here. Choose a reasonable voltage—say, one volt—and calculate the output voltage from the bridge at T1 and T3. This will give you a sensitivity for that particular supply voltage. Next, raise or lower V_S in proportion to the increase or decrease in sensitivity needed.

Remember that making the supply voltage too high will cause the thermistor to self-heat, causing measurement errors. For a typical small thermistor in air, one milliwatt of dissipation will cause a 1°C error. The power dissipation will be highest when the thermistor equals R1 and will be:

$$P_D = \frac{(0.5V_s)^2}{R1}$$

where P_D is in watts. For precise work you will want to keep the power dissipation to 0.1 milliwatt or less.

Table 2 lists the calculated resistor and supply-voltage values for three different temperature ranges. Notice that linearity is very good for narrow ranges, but gets worse rapidly as the temperature range widens. The thermistor used in this design is a Yellow Springs Instrument Co. (Box 465, Yellow Springs, OH 45387) model *44004*, 400-series probe. You will probably have to create series or parallel resistor combinations to obtain the calculated resistor values. Notice that the supply voltages have been chosen to give an output sensitivity of 10 millivolts-per-°C.

TABLE 2—EXAMPLES OF BRIDGE DESIGNS

Temperature range	10 to 30°C	0 to 50°C	0 to 70°C
Temperature for zero output	10°C	0°C	0°C
Sensitivity	10 mV/°C	10mV/°C	10 mV/°C
Bridge supply (V_s)	916.2 mV	1017.3 mV	1147.0 mV
R1	2,168 ohms	1,763 ohms	1,164 ohms
R2	4,482 ohms	7,355 ohms	7,355 ohms
R3	2,168 ohms	1,763 ohms	1,164 ohms
Maximum nonlinearity	+0.07 −0.06°C	+0.85 −0.95°C	+2.0 −2.3°C

Note: Thermistor is a YSI 44004, 400 series probe or equivalent, 2,252 ohms at 25°C.

A circuit like this, made from a few resistors and an adjustable supply (or a battery and voltage divider), is handy in the laboratory for reading temperature. The *44004* thermistor itself is accurate to 0.2 °C or better. Since sensitivity is about 4%-per-°C, a resistor or supply error of one percent causes a temperature error of only 0.25%. The bridge output may be read directly on a DVM, or fed into a high-impedance differential amplifier for other instrumentation needs. Calibration may be checked by substituting a precision decade box for the thermistor and, if need be, changed by adjusting R2 or R3 to set the zero point. The supply voltage can also be adjusted to set sensitivity.

Differential temperature, the difference between two temperatures, is often useful. For example, the difference between the inlet an outlet temperatures of a solar collector, heat exchanger, heat pump or air-conditioner coil measures operating efficiency. To read relative humidity, we must know the difference between wet-bulb and dry-bulb temperatures. You can measure differential temperature with the Wheatstone circuit by simply replacing R2 with a second thermistor. The two thermistors must be closely matched to obtain zero-bridge output at zero temperature difference. Precision interchangeable thermistors are recommended for this application.

Multiple-thermistor linear networks

The linear range may be widened considerably by using two thermistors. Figure 13 shows a two-thermistor bridge circuit that is linear to within ±.22°C from 0 to 100°C.

At very low temperatures, the resistance of thermistor R_{T2} is so large (95K at 0 °C) that it has very little effect on the circuit. The circuit behaves much like a 6K thermistor in series with a 6.25K fixed resistor, which has a linear range centered around 15°C. As the temperature increases, the resistance of thermistor R_{T2} drops and begins to shunt the R_{T1}-R2 combination. Thus, while the output sensitivity provided by R_{T1} is dropping off (the high end of the S curve in Fig. 12), R_{T2} begins providing an additional "boost". In the middle of the temperature range, both thermistors are influencing the output.

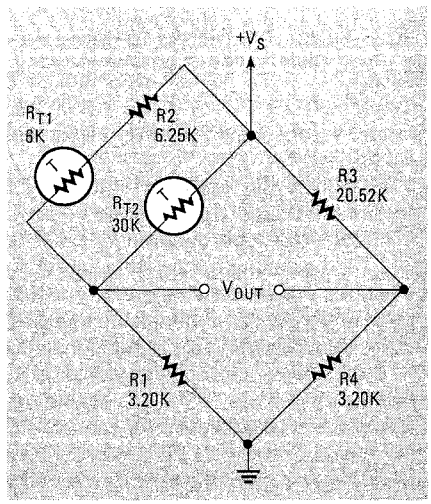


FIG. 13—A THERMISTOR-PAIR can be used in a Wheatstone bridge to improve the output linearity. This circuit is linear to within ±0.216°C from 0–100°C.

At higher temperatures, R_{T1} becomes so much smaller than the 6.25K resistor (408 ohms at 100 °C) that its effect is unimportant. Now the circuit behaves as if thermistor R_{T2} was in parallel only with R2. This combination has a linear region near 100 °C. Overall, as we raise the temperature from 0 to 100 °C, the influence of R_{T1} gradually decreases while the influence of R_{T2} increases, providing a linear output over a much wider range.

Selection of an optimum set of resistors and thermistors for the circuit shown in Fig. 13 is not easy. A lot of trial-and-error calculation is needed to find the best values, and it helps to use a computer program with the circuit equations and thermistor tables (or the Steinhart and Hart equation, discussed last month) built in. Fortunately, you don't have to do this. That's because at least two manufacturers sell preselected sets of resistors. We'll tell you who, and look at some more thermistor topics, next time. **R-E**

ALL ABOUT THERMISTORS

HARRY L. TRIETLEY

We conclude our look at thermistors with two simple but practical projects—a digital thermometer and a temperature-to-frequency converter—that you can build.

Part 3 BEFORE WE MOVE ON to our thermistor-based projects, let's finish up our discussion of matched thermistor sets.

At least two manufacturers, Yellow Springs Instrument Co. (Box 279, Yellow Springs, OH 45387) and Fenwal (63 Fountain St., Framingham, MA 01701), sell preselected and precalculated sets of components. The thermistor pair is constructed as a single component and looks just like an ordinary small, epoxy-coated disc, except that it has three leads instead of two. Internally, the two thermistors are connected in common on one side. The resistors are low temperature-coefficient, 0.1% metal film resistors.

Table 3 lists the values of four different component sets from the Yellow Springs Instrument Co. that are intended to be used with either the *44018* thermistor-pair or the 700-series thermistor probe. The selected values of R1 and R2 optimize the linearity over several temperature ranges. Table 3 also lists a *resistance mode* equation—we will get to this a bit later. The thermistor-pair itself has an accuracy of ±0.15 °C (±0.27 °F), which should be added to the linearity deviation to find worst-case error. Other prepackaged thermistor sets are available, including a three-thermistor set for even better linearity.

Table 4 lists the bridge component values (R3, R4, and V_S) needed for an output of 10 mV-per-°C or 5 mV-per-°F. You can get 10 mV-per-°F by doubling the supply voltage, but that's not recommended—the power dissipation in the thermistors may become high enough to affect accuracy.

Resistor-thermistor networks

It is often useful to create a network whose resistance changes linearly with temperature. Such networks are used to temperature-compensate other circuit values or to measure temperature using an ohmmeter-like circuit. An NTC thermistor may be linearized by simply connecting a resistor in parallel as shown in Fig. 14.

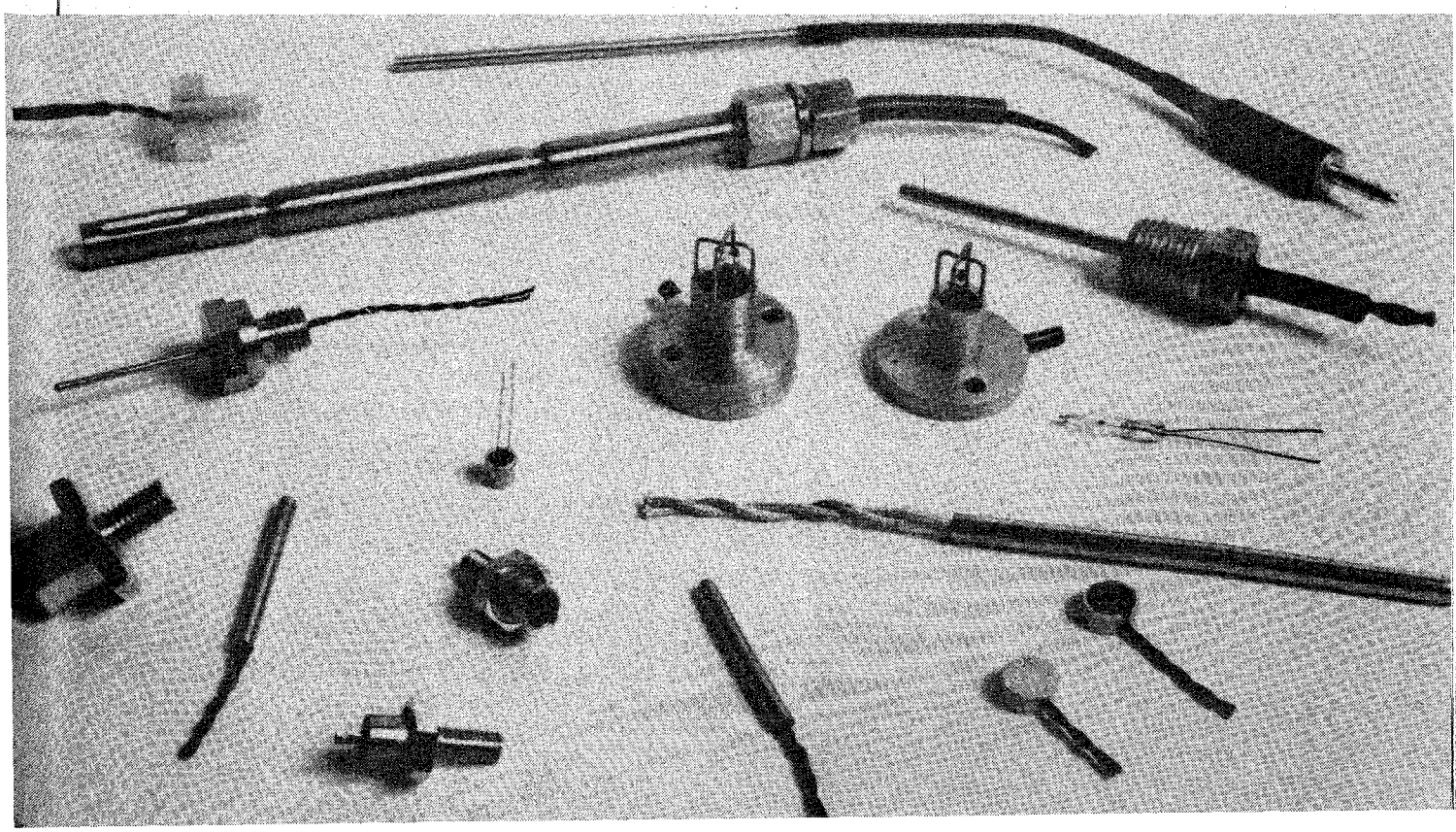


TABLE 3—MULTIPLE THERMISTOR LINEAR NETWORKS

Linear temperature range	R1	R2	Bridge equation* (V_{out}, volts, when V_s equals 1 volt.)	Resistance mode* equation (ohms)	Linearity deviation	Manufacturer's component set no.
0 to 100°C	3.20K	6.25K	0.0053483 T + 0.13493	2768.23 − 17.115 T	±0.216°C	YSI 44201
or			or	or	or	
32 to 212°F			0.00297127 T + 0.03985	3072.48 − 9.508 T	±0.388°F	
−5 to 45°C	5.70K	12.0K	0.0056846 T + 0.194142	4593.39 − 32.402 T	±0.065°C	YSI 44202
or			or	or	or	
23 to 113°F			0.0031581 T + 0.093083	5169.42 − 18.001 T	±0.12°F	
−30 to 50°C	18.7K	35.25K	0.0067966 T + 0.34893	12175 − 127.096 T	±0.16°C	YSI 44203
or			or	or	or	
−22 to 122°F			0.00377588 T + 0.228102	14435 − 70.608 T	±0.29°F	
−2 to 38°C	5.70K	12.4K	0.00563179 T + 0.192437	4603.11 − 32.1012 T	±0.03°C	YSI 44204
or			or	or	or	
30 to 100°F			0.0031289 T + 0.09232	5173.8 − 17.834 T	±0.055°F	

The values shown work with YSI 44018 thermistor-pair. Resistors must be 0.1% or better.

Bridge equation refers to Fig. 13. Resistance mode equation refers to Fig. 16.

Figure 15 shows the resistance-versus-temperature curve for such a network. You can see that it is the same S-shaped curve as was seen earlier for a thermistor bridge, only inverted. As it turns out, the same rules apply for linearization: you can get good linearization over narrow ranges by simply choosing the resistor to be equal to the thermistor's value at mid-scale. For best possible linearization, you can use the same equation as was used earlier to linearize the bridge.

Table 5 lists the resistance equations and linearity deviation for three temperature ranges. Just as with the bridge, linearity becomes worse as the temperature range increases. Of course, sensitivity and zero-offset are not adjustable, although you can add a resistor in series with the network without affecting linearity. Only negative-going slopes are possible, since the thermistors' resistance decreases with increasing temperature.

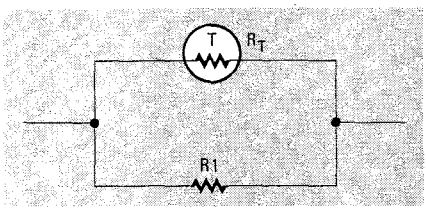


FIG. 14—A THERMISTOR'S RESISTANCE can be linearized over small temperature ranges simply by placing a fixed resistor in parallel with it.

Networks like those are useful if you need to generate a gain or an offset voltage that changes with temperature. They also may be used in series with a coil such as a meter-movement or a TV deflection coil. Since the resistance of copper increases with temperature, the series thermistor network can be designed to keep the total resistance constant despite temperature fluctuations.

For best linearity over wide temperature ranges, two thermistors (or a single thermistor-pair) can be used as shown in Fig. 16. The resistor values for the circuit shown in Fig. 16 turn out to be the same as were used earlier in the bridge circuit. Therefore, you can use the same pre-selected component sets that are available from the manufacturers. Table 3 can again be used to select the optimum value of R1 and R2. The total resistance of that circuit is calculated using the resistance-mode equation listed in Table 3.

Analog-to-digital conversion

You can connect the output of a thermistor bridge directly to the input of an

TABLE 4—LINEAR BRIDGE COMPONENTS

Temperature range	Resistors R3, R4	Supply voltage V_s	Bridge output
0 to 100°C	20.52K, 3.20K	1.8698 V	10 mV/°C
32 to 212°F	77.10K, 3.20K	1.6828 V	5 mV/°F
−5 to 45°C	23.66K, 5.70K	1.7591 V	10 mV/°C
23 to 113°F	55.54K, 5.70K	1.5832 V	5 mV/°F
−30 to 50°C	34.89K, 18.7K	1.4713 V	10 mV/°C
−22 to 122°F	63.28K, 18.7K	1.3242 V	5 mV/°F
−2 to 38°C	23.92K, 5.70K	1.7756 V	10 mV/°C
30 to 100°F	56.04K, 5.70K	1.5980 V	5 mV/°F

Note: Resistors should be 0.1% or better. For values of R1 and R2 see Table 2a.

TABLE 5—LINEARIZED THERMISTOR-RESISTOR NETWORK VALUES

Temperature range	R1	Linear resistance equation (ohms)	Linearity deviation
10 to 30°C	2,168 ohms	1697.84 − 23.664 T	+0.07, −0.06°C
0 to 50°C	1,763 ohms	1422.12 − 17.330 T	+0.86, −0.95°C
0 to 70°C	1,164 ohms	1004.96 − 10.147T	+2.0, −2.3°C

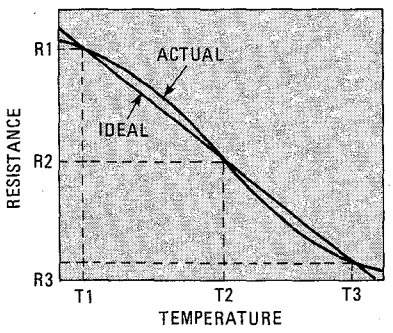


FIG. 15—RESISTANCE VS. TEMPERATURE of the resistor-thermistor combination of Fig. 4

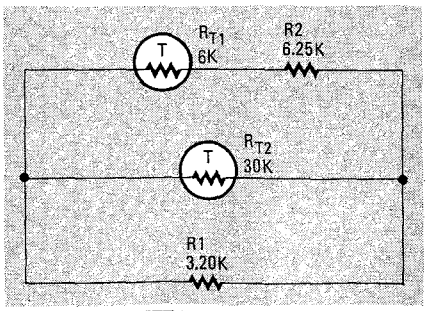


FIG. 16—FOR BETTER LINEARITY, you can use two thermistors in parallel. This circuit provides a linearity of ±0.216°C from 0–100 °C.

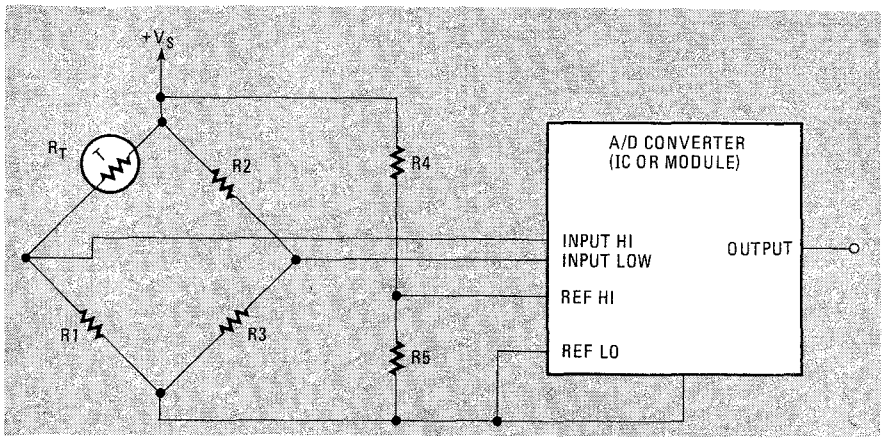


FIG. 17—CONNECTING THE BRIDGE OUTPUT to an A/D converter provides digital temperature information.

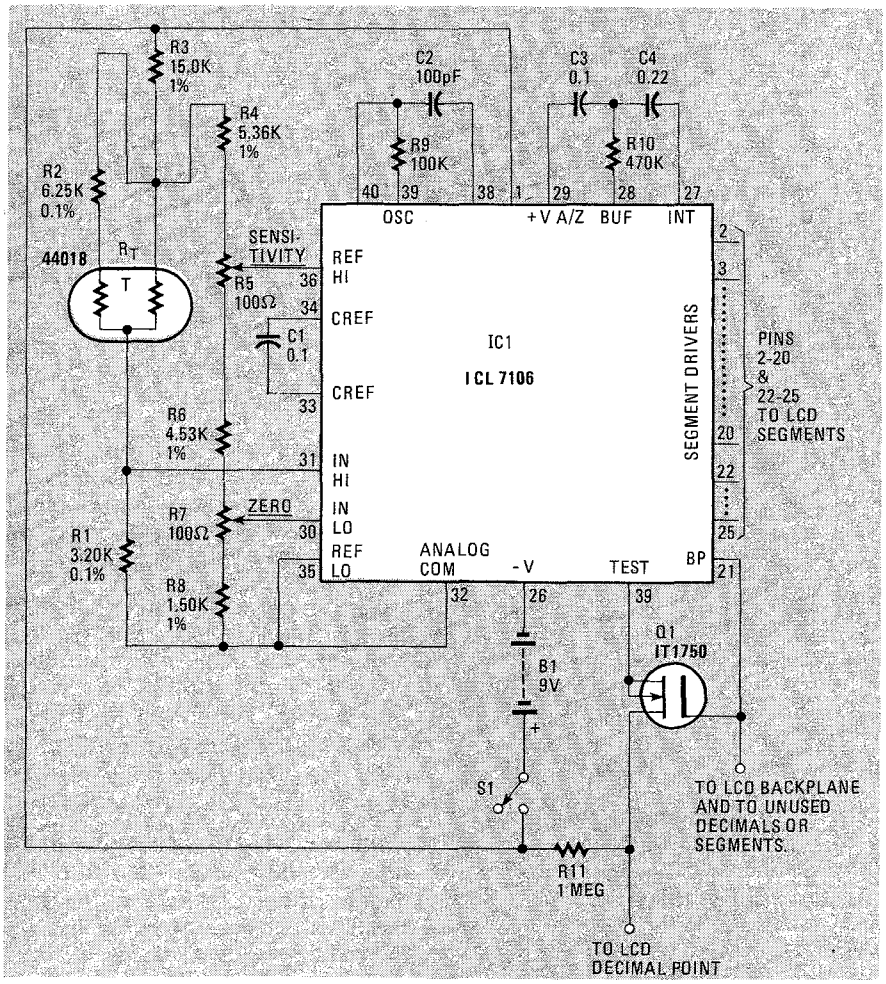


FIG. 18—A BATTERY-POWERED DIGITAL THERMOMETER using a single IC and a thermistor-pair.

analog-to-digital converter IC or module as shown in Fig. 17. The bridge values are selected as before to provide best linearity, needed voltage sensitivity, zero offset, etc. Either a single thermistor or a thermistor-pair may be used, and the component values of Tables 2 and 3 will work just as well here. The reference voltage input should be set for the desired sensitivity or for the desired full-scale output.

One interesting observation results from the fact that an analog-to-digital converter is really a ratio device; that is,

$$\text{Output} = K \times \frac{\text{Input}}{\text{Reference}}$$

If the supply voltage, V_S, varies, the input and reference voltages will vary by equal percentages, leaving the output unchanged. That means that the regulation, and even the exact value of V_S, are not critical—an inexpensive zener diode or regulator may be used. In fact, if the circuit's power supply is only moderately regulated, you may be able to use a simple voltage divider to create V_S. We will see this in the next example. A very simple circuit can give accurate and stable results.

Digital thermometer

If we replace the A/D converter with an digital voltmeter IC, we can produces a simple, accurate, battery-powered thermometer. Figure 18 shows the complete circuit we need. It uses an Intersil ICL7106 A/D converter IC and a two-thermistor linear network.

The thermistor-pair R_T forms the left-hand side of a Wheatstone bridge. The right-hand side of the bridge is formed by the voltage-divider string R4 through R8. That same string provides the reference voltage for the A/D converter.

The ICL7106 maintains its ANALOG COMMON (pin 32) 2.8 volts below the supply voltage. Resistor R3 reduces the voltage for the bridge, to minimize thermistor self-heating. You will notice that the bridge voltage varies as the thermistors change with temperature, from about one volt at 0°C to 0.5 volt at 100°C. In a normal analog situation, that would be disastrous. In this case, however, the A/D converter's output equals the input divided by the reference and, since the input and reference vary by equal percentages, the output is unaffected.

The IC itself is a dual-slope A/D converter with an auto-zero cycle. Its output will directly drive a 3-1/2-digit, seven-segment LCD readout. The output (as seen on the display) is given by:

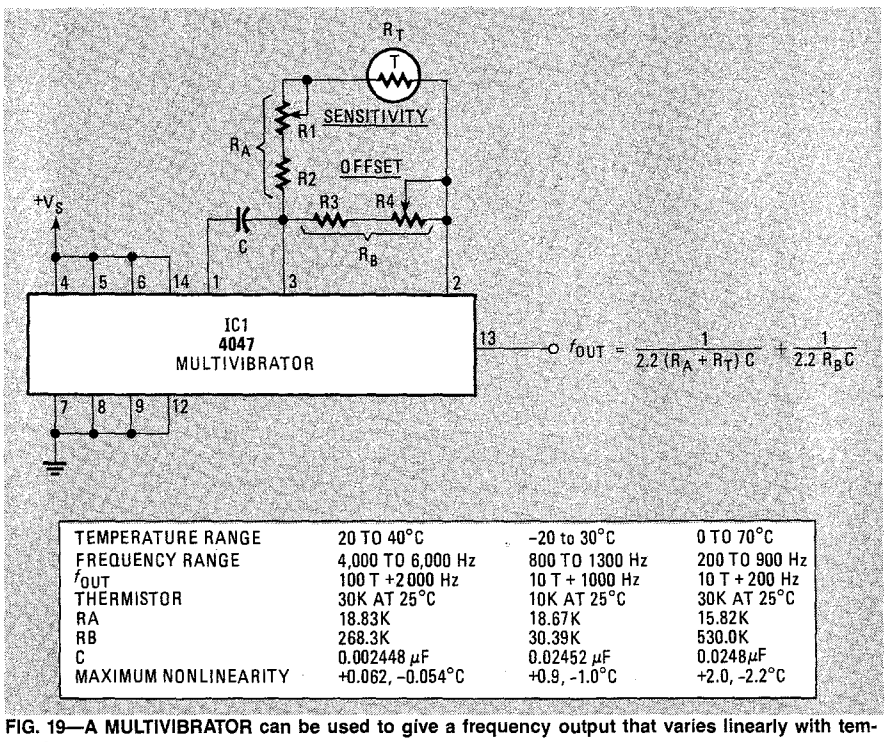
$$\text{Output} = \frac{\text{Input}}{\text{Reference}} \times 1000$$

The IC's clock timing is set by R9 and C2 to 48 kHz, which results in three readings per second. Transistor Q1 inverts the backplane waveform to drive the decimal point. The thermistor-pair shown is a 44018 or 700-series probe from Yellow Springs Instrument Co.

To calibrate the thermometer, you first have to know the R versus T values of the thermistor-pair. That information is shown in Table 6. Once you know their characteristics, you can replace two thermistors of the pair with accurate, known resistances (from precision decade resistors, for example). Set both to the zero-degree resistances, then adjust R7 (zero control) for a reading of 0.2 (the setting for minimum nonlinearity error). Next, set the decades to 100°C and adjust R5 (sensitivity) until the reading is 100.0. Repeat as necessary.

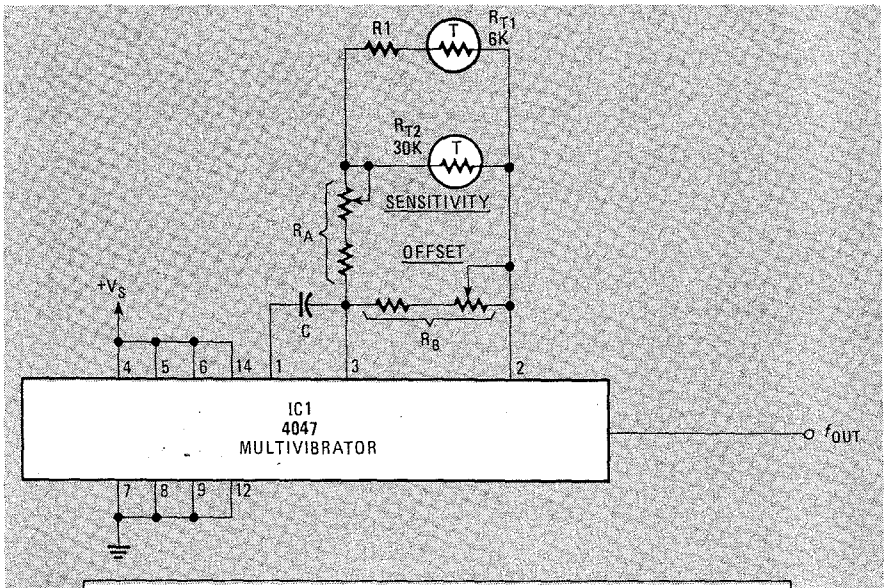
Temperature to frequency converters

You can make a temperature-to-frequency converted by replacing the A/D converter of Fig. 17 with a voltage-to-



TEMPERATURE RANGE	20 TO 40°C	-20 to 30°C	0 TO 70°C
FREQUENCY RANGE	4,000 TO 6,000 Hz	800 TO 1300 Hz	200 TO 900 Hz
f_{OUT}	100 T +2000 Hz	10 T + 1000 Hz	10 T + 200 Hz
THERMISTOR	30K AT 25°C	10K AT 25°C	30K AT 25°C
RA	18.83K	18.67K	15.82K
RB	268.3K	30.39K	530.0K
C	0.002448 μF	0.02452 μF	0.0248μF
MAXIMUM NONLINEARITY	+0.062, -0.054°C	+0.9, -1.0°C	+2.0, -2.2°C

FIG. 19—A MULTIVIBRATOR can be used to give a frequency output that varies linearly with temperature.



TEMPERATURE RANGE	0 TO 100°C	-5 TO 45°C	-30 TO 50°C
FREQUENCY RANGE	1000 TO 2000 Hz	4500 TO 9500 Hz	700 TO 1500 Hz
f_{OUT}	10T + 1000 Hz	100 T + 5000 Hz	10 T + 1000 Hz
RA	3.2K	5.7K	18.7K
R1	6.25K	12K	35.25K
RB	8K	63.28K	56.55K
C	0.07597 μF	0.004533 μF	0.01652 μF
LINEARITY	±0.216°C	±0.065°C	±0.16°C

FIG. 20—USING TWO THERMISTORS improves the linearity of the temperature-to-frequency converter of Fig. 19

frequency converter. Even simpler and less expensive, though, is a circuit that uses a thermistor as part of the resistance in an R-C multivibrator circuit.

Temperature-to-frequency converters are useful in telemetry applications because the frequency signal is not affected by line resistance or by normal amounts of noise pickup. They are especially useful if temperature data must be transmitted by RF, through telephone lines or optical cable, (where D.C. transmission is impossible). The frequency range can be tailored to suit the transmission medium.

Figure 19 shows a temperature-to-frequency converter built around a 4047 CMOS multivibrator IC. The 4047's output frequency (pin 13) is given by $f = 1/(2.2RC)$. Therefore:

$$f = \frac{1}{2.2\,(R_A + R_T)C} + \frac{1}{2.2\,(R_B)C}$$

The combination of R_A and C affects the circuit's sensitivity, while R_B affects only the frequency offset. Resistor R1 is selected using:

$$R_A = \frac{R_{T1}R_{T2} + R_{T2}R_{T3} - 2R_{T1}R_{T3}}{R_{T1} + R_{T3} - 2R_{T2}}$$

where R_{T1}, R_{T2}, and R_{T3} are the thermistor's resistances at the low-end, mid-scale, and high-end temperatures, respectively. Linearity is the same as shown in Fig. 12.

A high-resistance thermistor should be used for this temperature-to-frequency converter. Depending on the supply voltage, the 4047 will generate several volts between terminals 2 and 3, and a low resistance thermistor will self-heat enough to cause large errors. Once the thermistor and the temperature range are chosen, compute R_A for best linearity.

Next, the capacitor must be chosen to give the right sensitivity (Hertz per degree). In the circuit shown:

$$C = \frac{1}{2.2S}\left[\frac{1}{R_A + R_{T3}} - \frac{1}{R_A + R_{T1}}\right]\left[\frac{1}{T3 - T1}\right]$$

where S has the units of Hz/°C, C is in farads and all resistances are in ohms. Finally, R2 is found by substituting R_A, R_{T1} and C in the original frequency equation and solving for the value of R_B that gives the desired frequency at T1. Figure 19 includes a table of component values for three temperature ranges. Notice that the calculations generally produce odd component values. The needed value of C must be created by using a parallel combination of capacitors; R_A and R_B include trimmer potentiometers.

Just as with the bridge, linearity and range of the temperature-to-frequency converter may be improved by using a two-thermistor network. The design process is complex, but Fig. 20 shows such a circuit. **R-E**

TABLE 6—R VERSUS T VALUES

Temperature	T1 (6K @ 25°C)	T2 (30K @ 25°C)
−30°C (−22°F)	106.2K	481.0K
−20°C (−4°F)	58.26K	271.2K
−10°C (14°F)	33.20K	158.0K
0°C (32°F)	19.59K	94.98K
10°C (50°F)	11.94K	58.75K
20°C (68°F)	7496 ohms	37.30K
30°C (86°F)	4834 ohms	24.27K
40°C (104°F)	3196 ohms	16.15K
50°C (122°F)	2162 ohms	10.97K
60°C (140°F)	1493 ohms	7599 ohms
70°C (158°F)	1051 ohms	5359 ohms
80°C (176°F)	753.8 ohms	3843 ohms
90°C (194°F)	549.8 ohms	2799 ohms
100°C (212°F)	407.6 ohms	2069 ohms